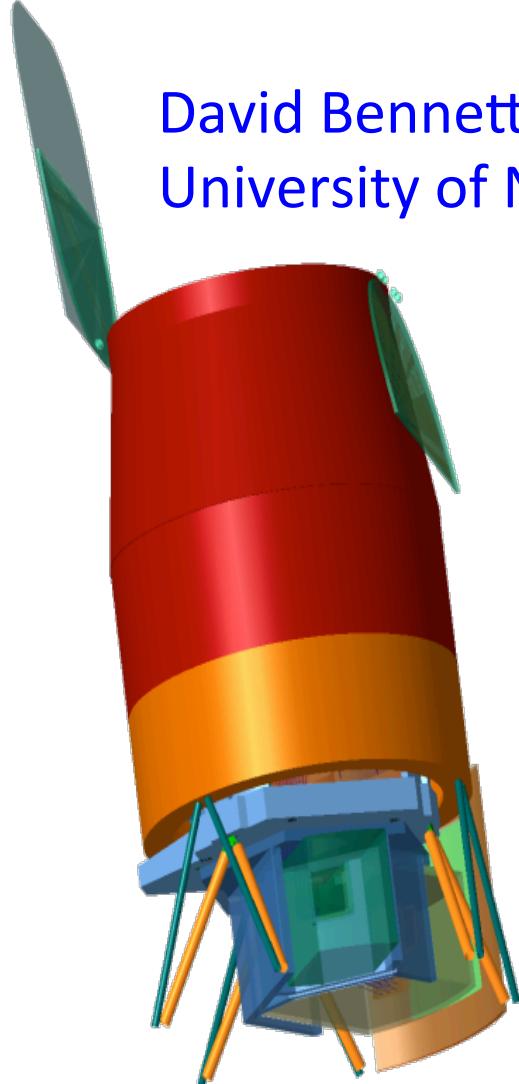


WFIRST-AFTA Exoplanet Microlensing

(Wide Field Infrared Survey Telescope -
Astrophysics Focused Telescope Assets)



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University of Notre Dame

SCIENCE DEFINITION TEAM

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WFIRST-AFTA Exoplanet Science

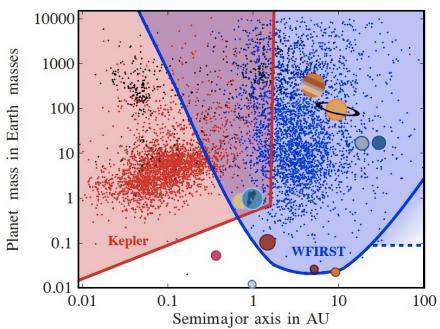
The combination of microlensing and direct imaging will dramatically expand our knowledge of other solar systems and will provide a first glimpse at the planetary families of our nearest neighbor stars.

Microlensing Survey

Monitor 200 million Galactic bulge stars every 15 minutes for 1.2 years

2800 cold exoplanets
300 Earth-mass planets
40 Mars-mass or smaller planets
40 free-floating Earth-mass planets

Complete the Exoplanet Census



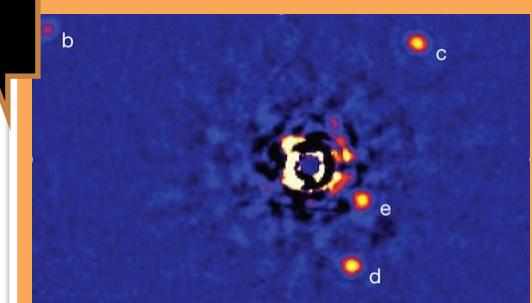
High Contrast Imaging

Survey up to 200 nearby stars for planets and debris disks at contrast levels of 10^{-9} on angular scales $> 0.2''$
 $R=70$ spectra and polarization between 400-1000 nm

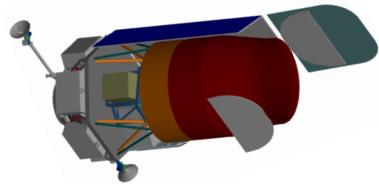
Detailed characterization of up to a dozen giant planets.
Discovery and characterization of several Neptunes
Detection of massive debris disks.

- How diverse are planetary systems?
- How do circumstellar disks evolve and form planetary systems?
- Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?

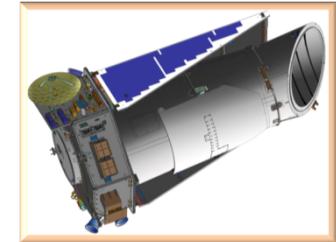
Discover and Characterize Nearby Worlds



Exoplanet Microlensing Survey

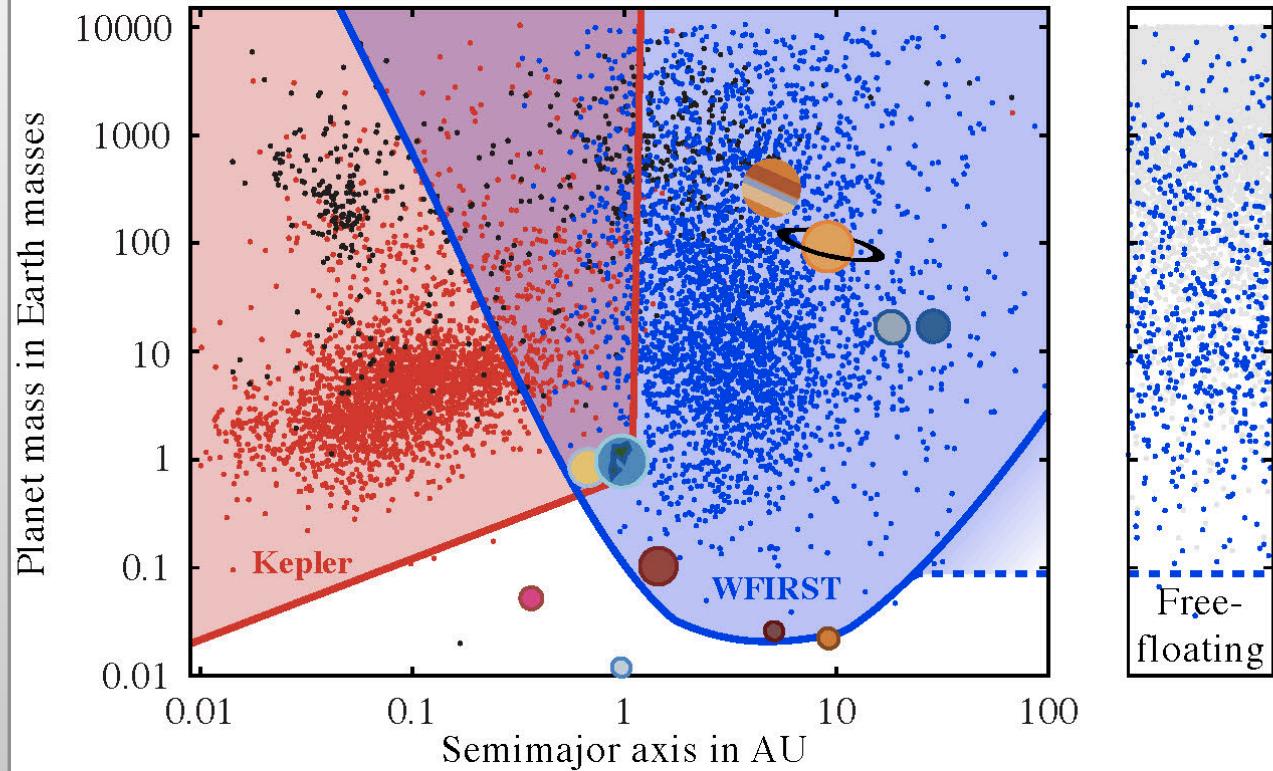


Together, Kepler and WFIRST-AFTA complete the statistical census of planetary systems in the Galaxy.



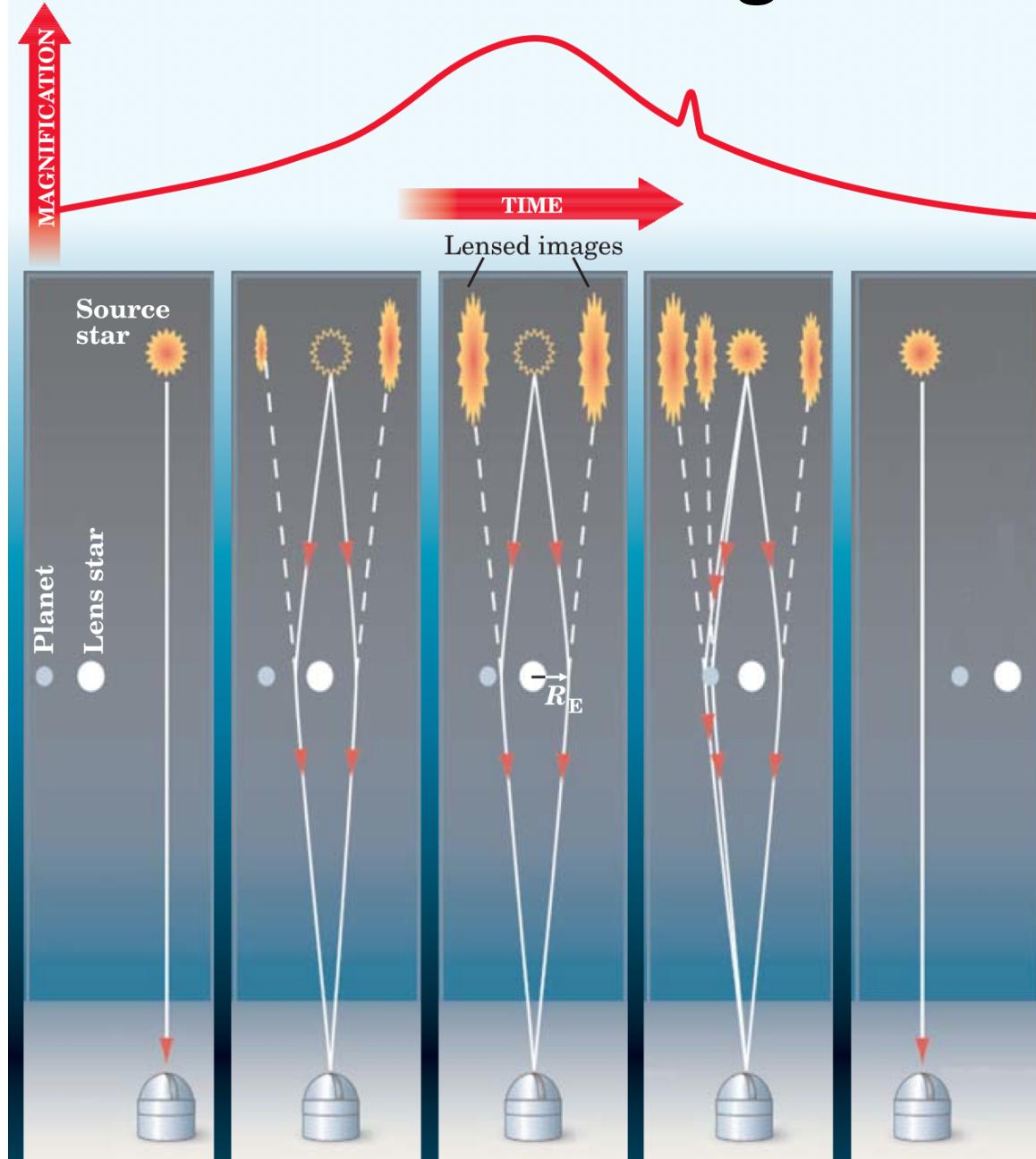
WFIRST-AFTA will:

- Detect 2800 planets, with orbits from the habitable zone outward, and masses down to a few times the mass of the Moon.
- Be sensitive to analogs of all the solar system's planets except Mercury.
- Measure the abundance of free-floating planets in the Galaxy with masses down to the mass of Mars

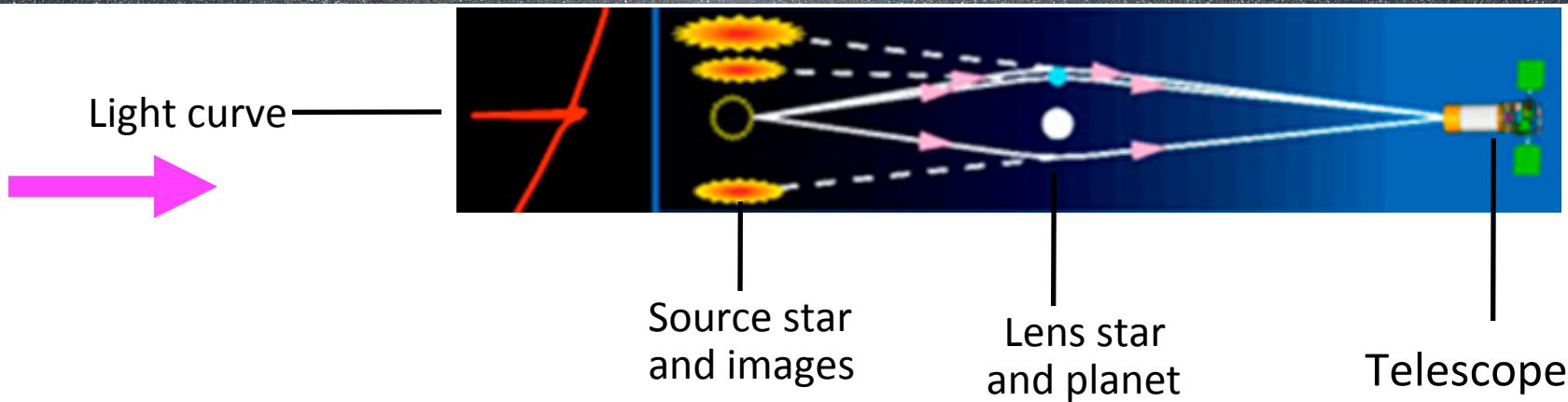
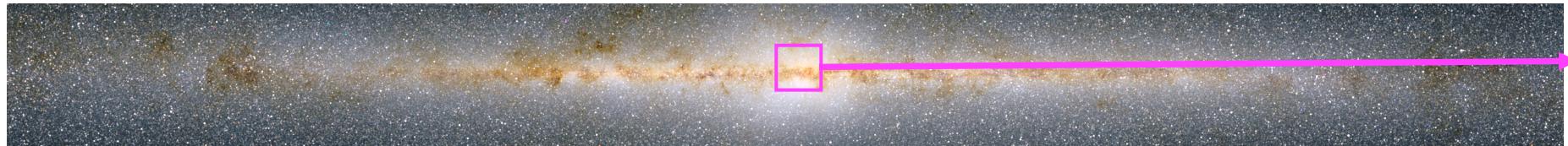
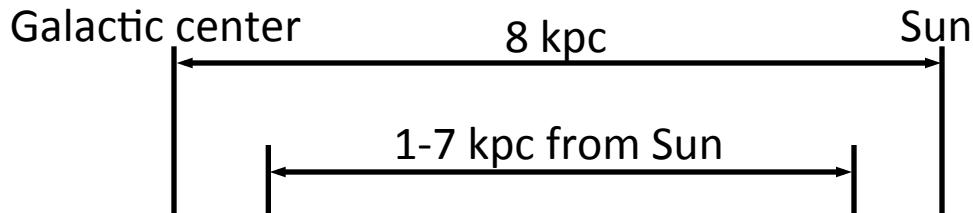


The Physics of Microlensing

- Foreground “lens” star + planet bend light of “source” star
- Bending angle = $4GM/(rc^2)$
- Multiple distorted images
 - Only total brightness change is observable
- Sensitive to planetary mass
- Low mass planet signals are rare – not weak
- Stellar lensing probability $\sim a few \times 10^{-6}$
 - Planetary lensing probability $\sim 0.001-1$ depending on event details
- Peak sensitivity is at 2-3 AU: the Einstein ring radius, R_E

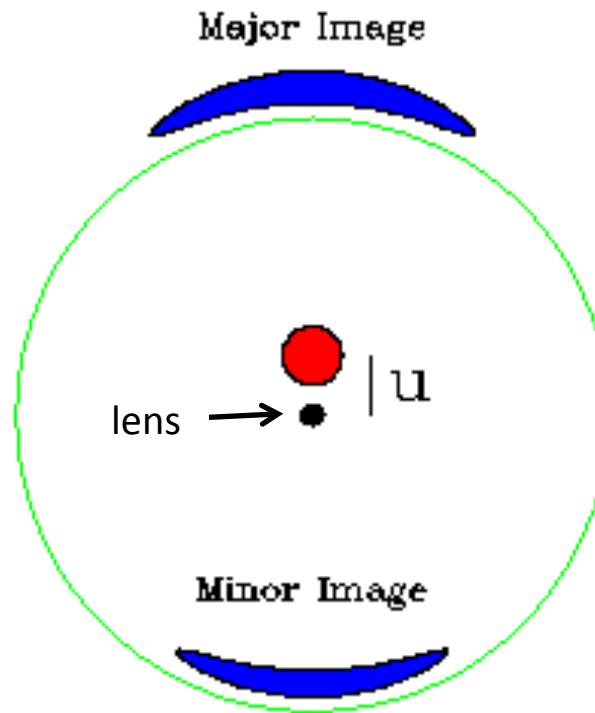
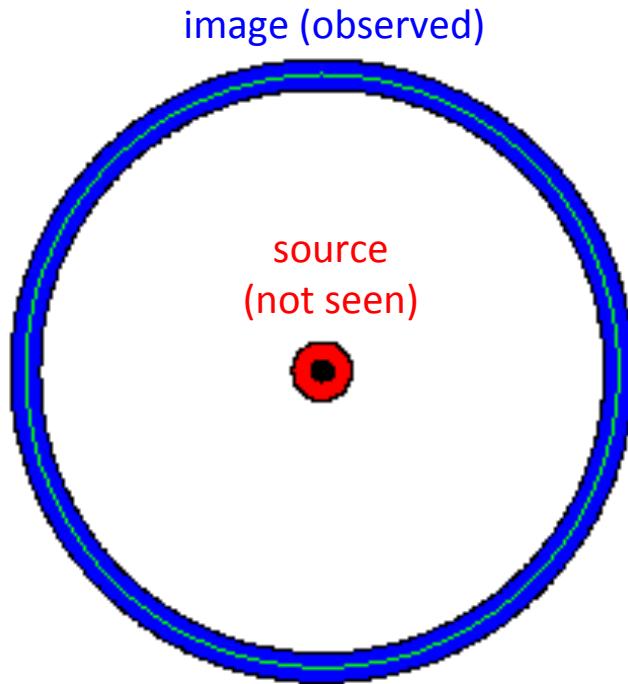


Microlensing Target Fields are in the Galactic Bulge



100s of millions of stars in the Galactic bulge in order to detect planetary companions to stars in the Galactic disk and bulge.

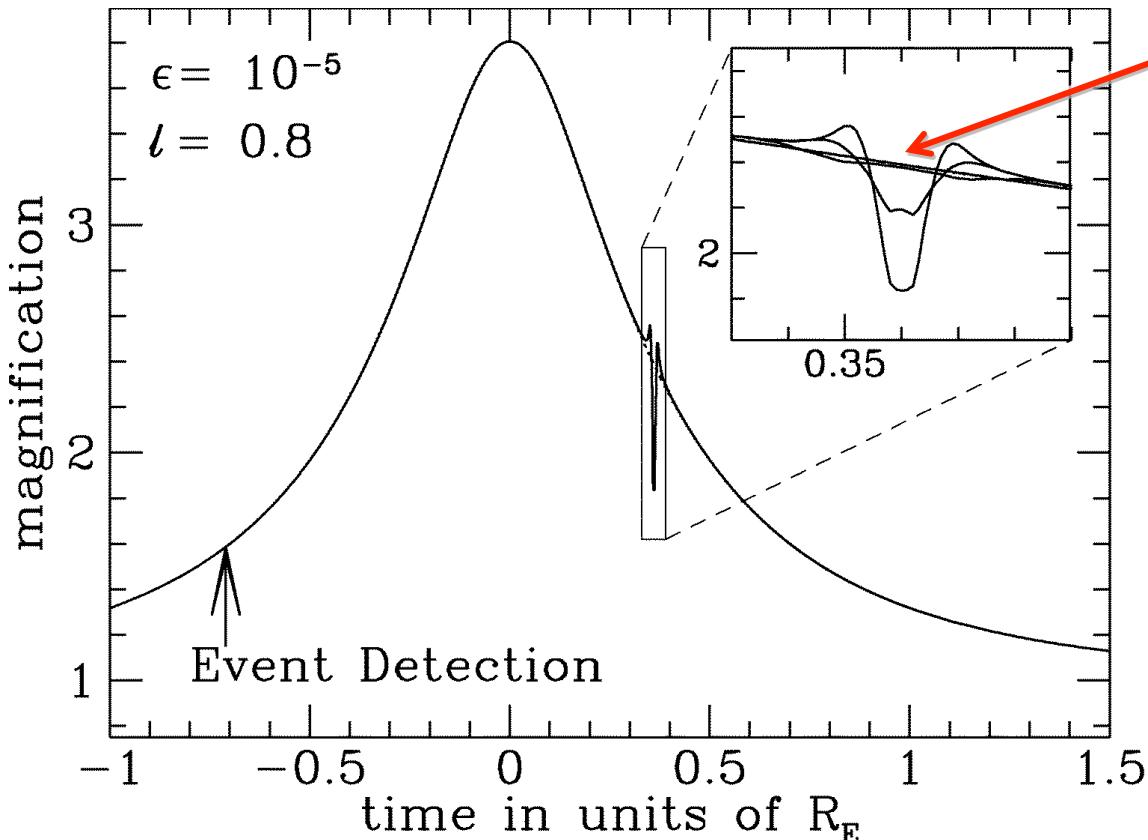
Lensed Images (Einstein 1936)



When source is distant, we see distorted, magnified images. If the alignment is perfect, we see an “Einstein Ring”. Planets are easiest to detect when they are located near the Einstein Ring, which is typically at 2-3 AU.

How Low Can We Go?

No signal for
giant sources



(Bennett & Rhie 1996)

For $\theta_E \geq \theta_*$:

low-mass planet signals are rare
and brief, but not weak

Limited by Source Size
angular Einstein radius

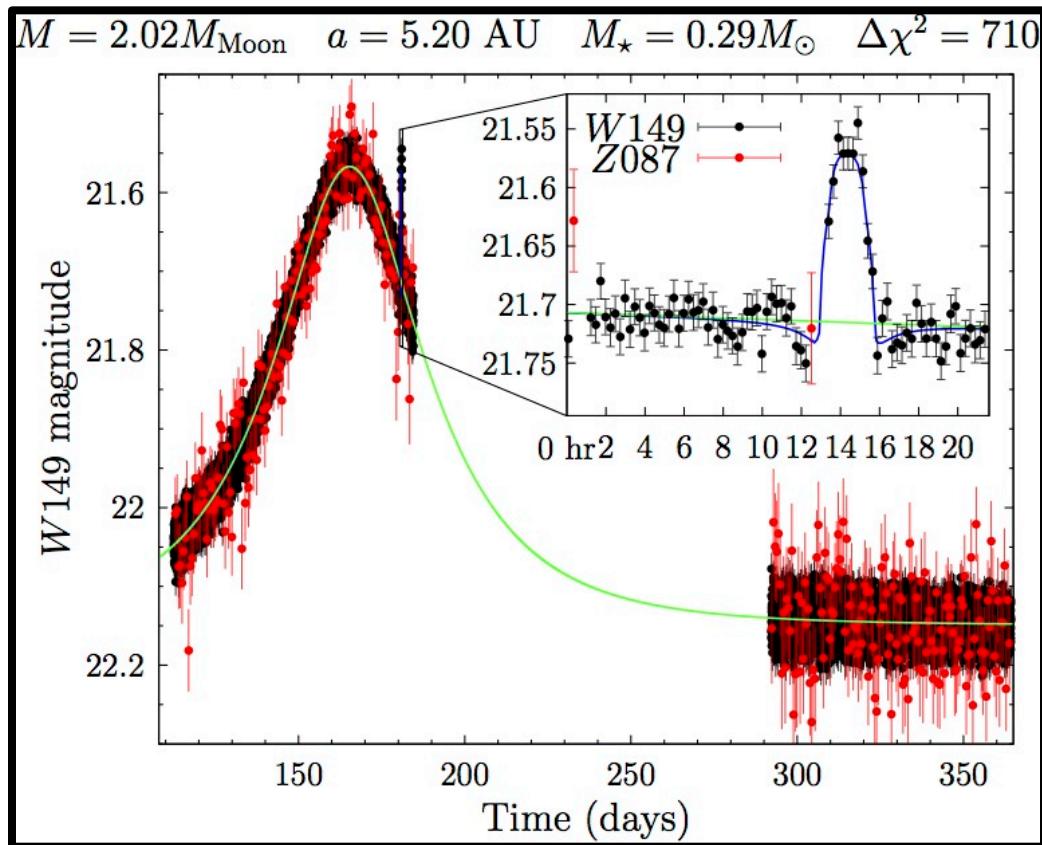
$$\theta_E \approx \mu\text{as} \left(\frac{M_p}{M_\oplus} \right)^{1/2}$$

$$\theta_* \approx \mu\text{as} \left(\frac{R_*}{R_\odot} \right)$$

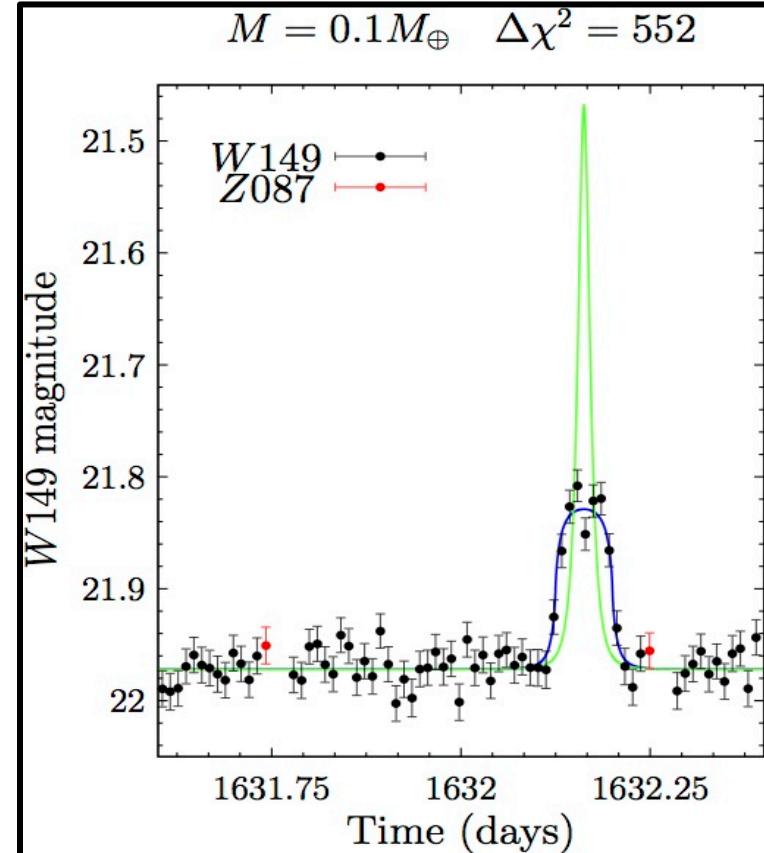
angular source star radius

Mars-mass planets
detectable
*if solar-type sources can be
monitored!*

Low-mass Planets Found with Main Sequence Sources

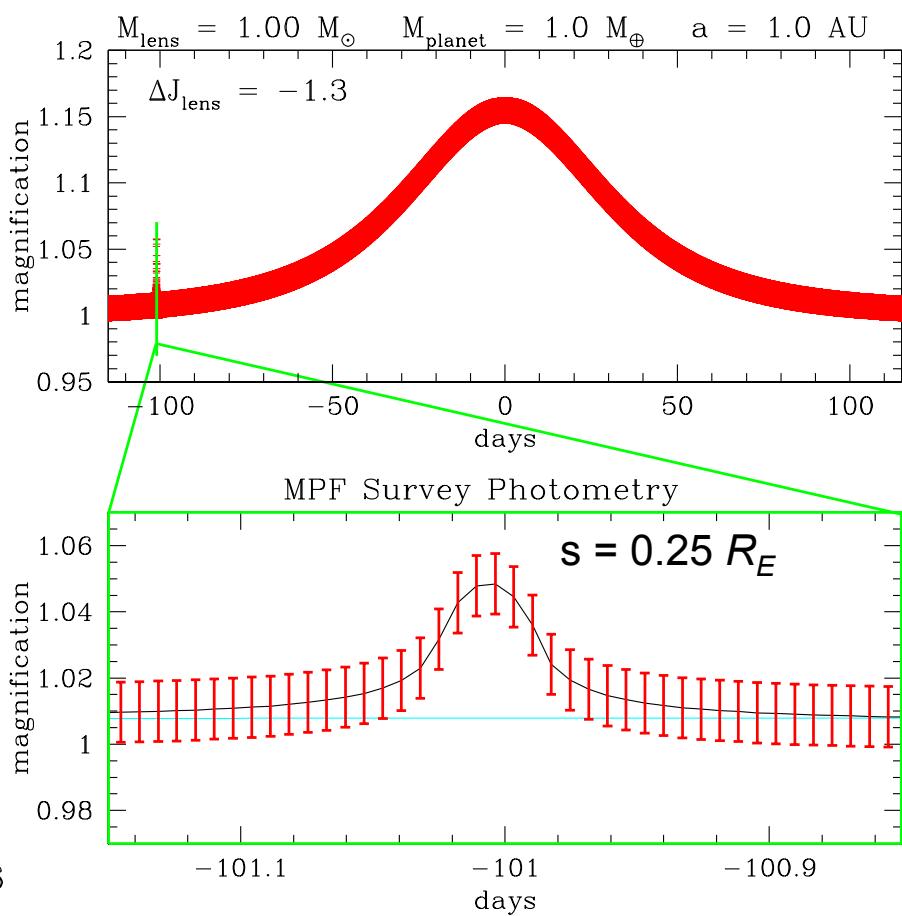
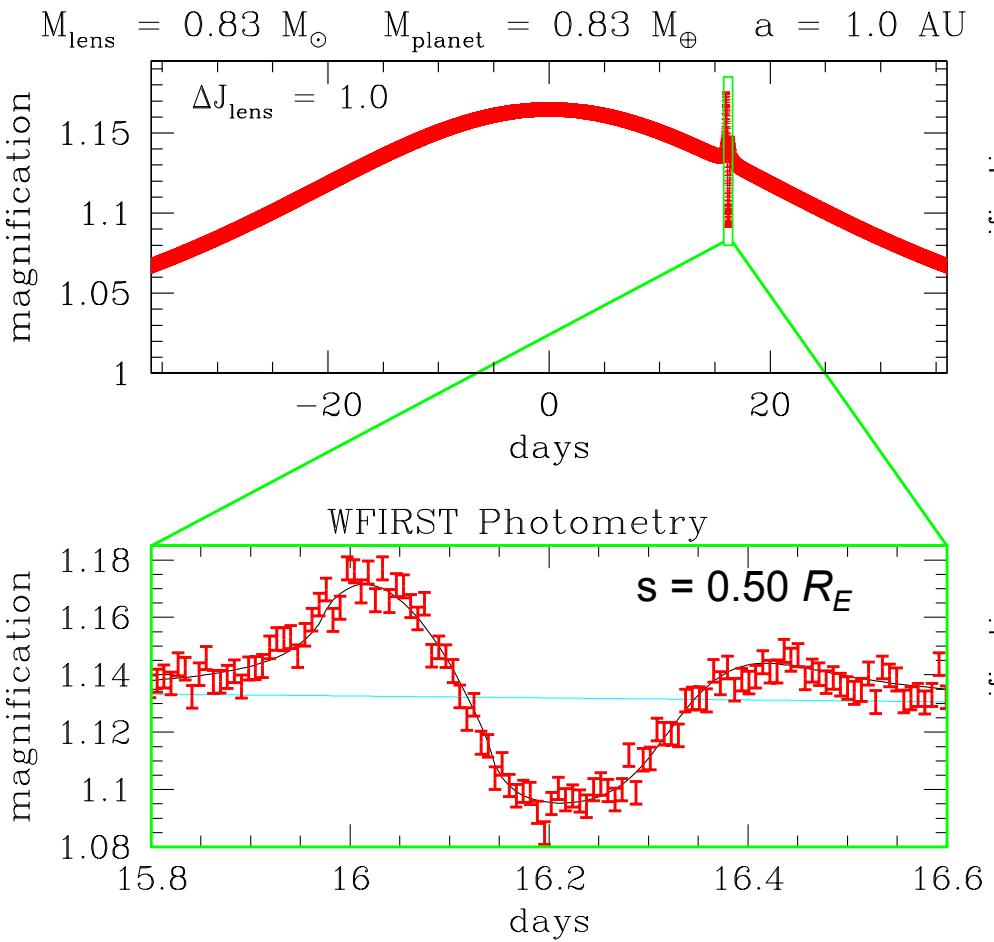


2 × Mass of the Moon @ 5.2 AU
(~27 sigma)



Free floating Mars
(~23 sigma)

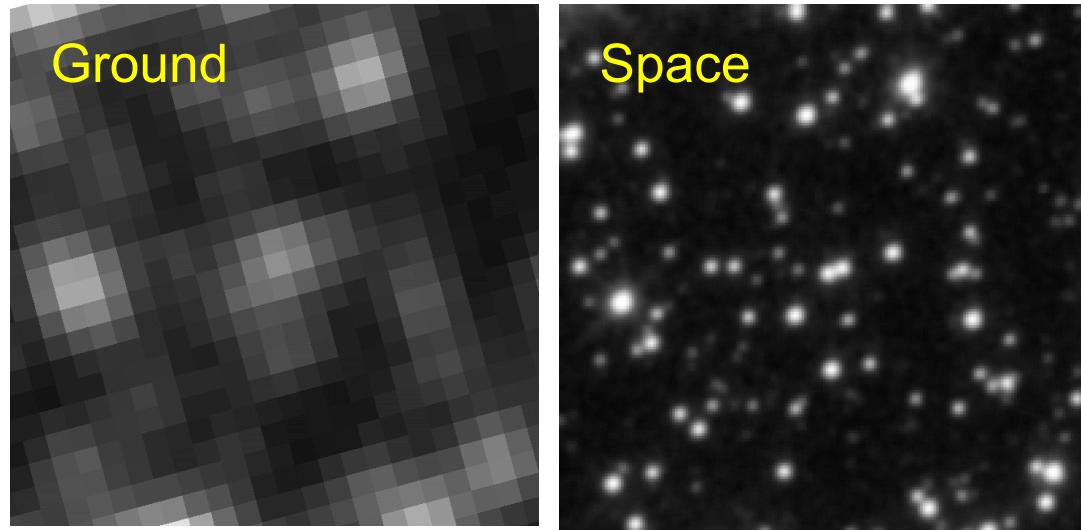
Close (HZ) Planets Found at Low Magnification



- Faint main sequences sources needed to detecting low-mass planets
- At separations $< R_E$, planetary signals occur at low stellar magnification
- Matthew Penny's talk from yesterday

Ground vs. Space Microlensing

- Infrared.
 - More extinguished fields with higher event rates
 - Smaller sources.
- Resolution.
 - Low-magnification events.
 - Isolate light from the lens star.
- Visibility.
 - Complete coverage.
- Smaller systematics.
 - Better characterization.
 - Robust quantification of sensitivities.

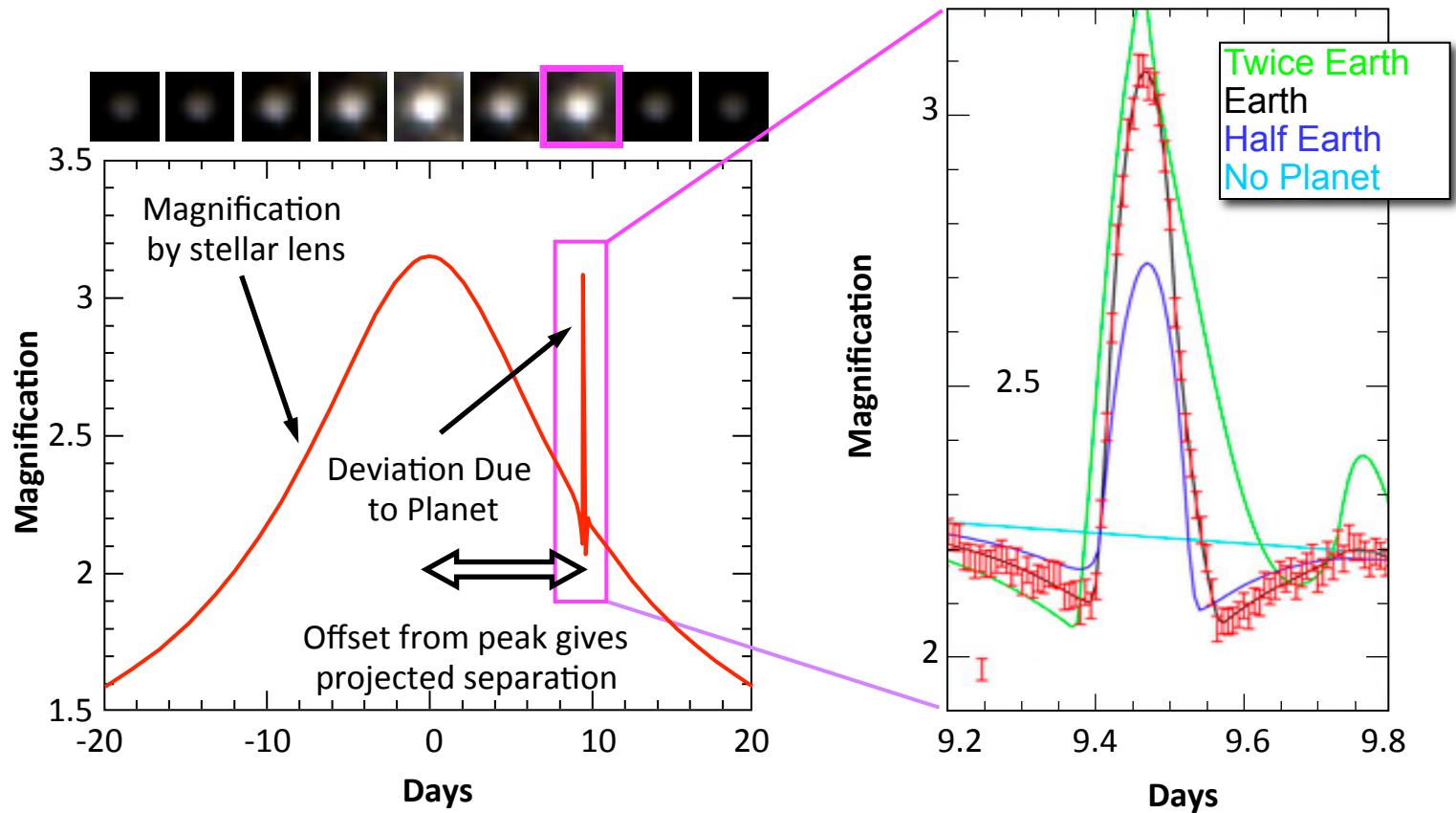


The field of microlensing event
MACHO 96-BLG-5
(Bennett & Rie 2002)

Science enabled from space: sub-Earth mass planets, habitable zone planets, free-floating Earth-mass planets, mass measurements.

Extraction of Exoplanet Light Curve Signal

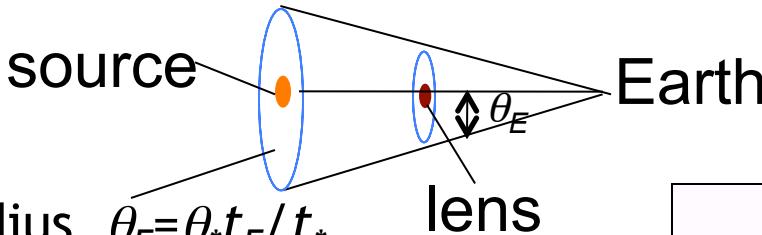
Time-series photometry is combined to uncover light curves of background source stars being lensed by foreground stars in the disk and bulge.



Planets are revealed as short-duration deviations from the smooth, symmetric magnification of the source due to the primary star.

Detailed fitting to the photometry yields the parameters of the detected planets.

Finite Source Effects & Microlensing Parallax Yield Lens System Mass



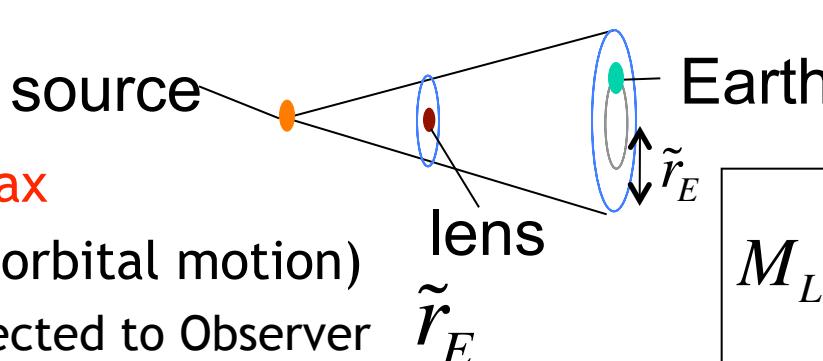
- Finite source effects

Angular Einstein radius $\theta_E = \theta_* t_E / t_*$

θ_* = source star angular radius

D_L and D_S are the lens and source distances

$$M_L = \frac{c^2}{4G} \theta_E^2 \frac{D_S D_L}{D_S - D_L}$$



- Microlensing Parallax

(Effect of Earth's orbital motion)

Einstein radius projected to Observer

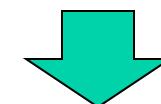
OR

- One of above +

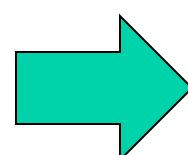
Lens brightness & color(AO,HST)

mass-distance relation $\rightarrow D_L$

$$M_L = \frac{c^2}{4G} \tilde{r}_E^2 \frac{D_S - D_L}{D_S D_L}$$



$$M_L = \frac{c^2}{4G} \tilde{r}_E \theta_E$$



HST Relative Proper Motion for OGLE-2005-BLG-169 Lens-Source

Source looks elongated relative to neighbors at 6.5 years after event

$$M_* = 0.69 \pm 0.02 M_{\odot}$$

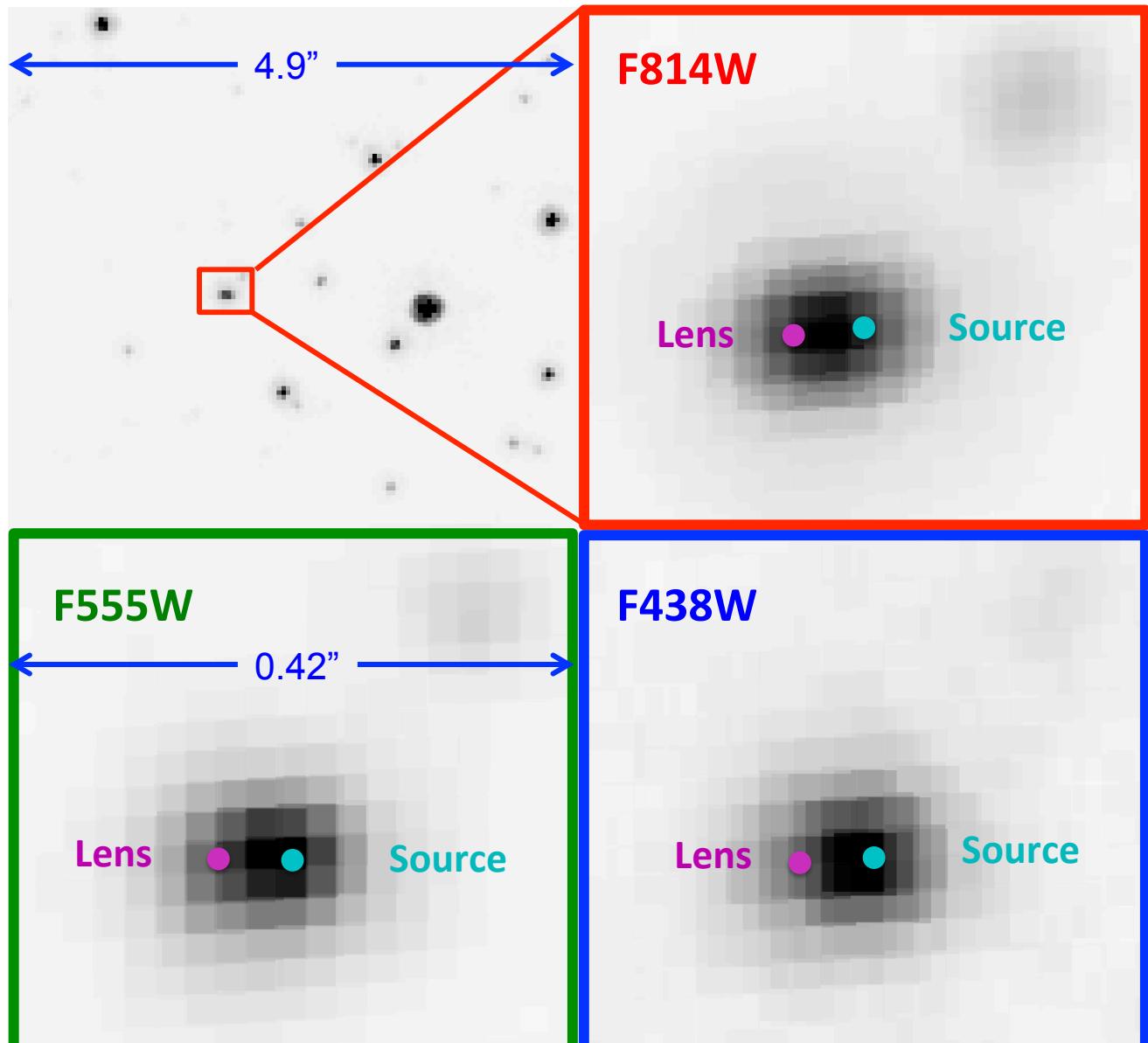
$$m_p = 14.1 \pm 0.9 M_{\oplus}$$

$$a_{\perp} = 3.5 \pm 0.3 \text{ AU}$$

$$a_{3d} = 4.0^{+2.2}_{-0.6} \text{ AU}$$

$$D_L = 4.1 \pm 0.4 \text{ kpc}$$

Bennett et al. 2015
Keck result:
Batista et al. 2015



Rogue Planet Population



OGLE

Sumi et al. (2011)
Nature, 473, 349

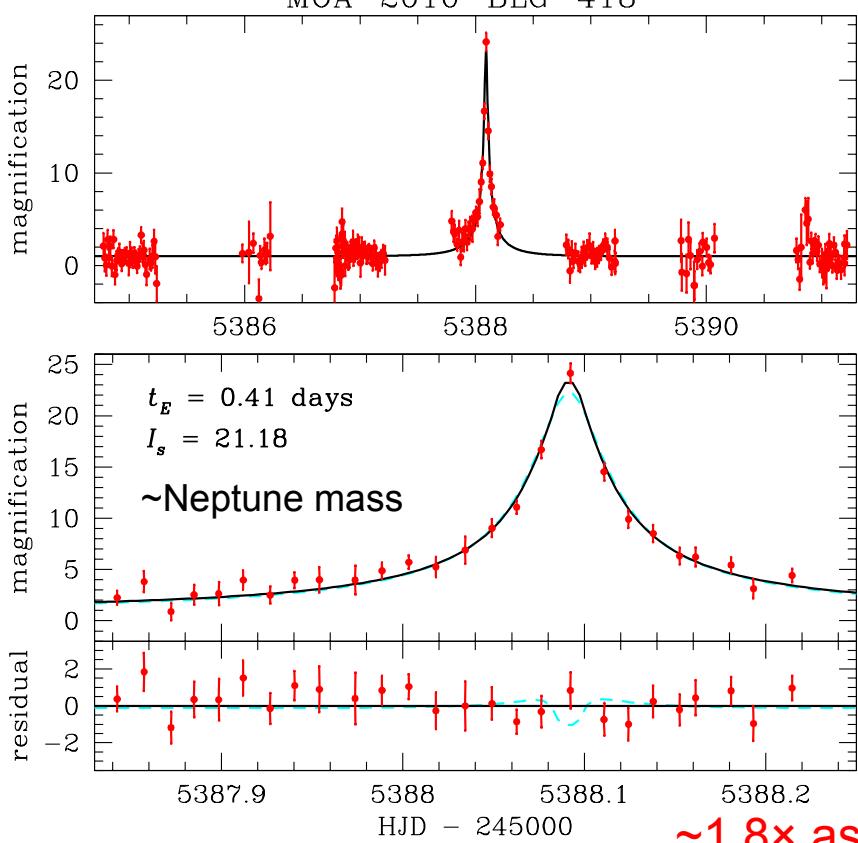
The cover of the June 2012 issue of Astronomy magazine. At the top, it says "HOW to view June's rare transit of Venus p. 50" and "June 2012". The title "Astronomy" is in large yellow letters, with "The world's best-selling astronomy magazine" below it. The main feature article is titled "WHY BILLIONS OF ROGUE PLANETS DRIFT THROUGH SPACE p. 24". Other headlines include "The 6 most important numbers in the universe p. 30", "Inside the Large Hadron Collider p. 44", "PLUS!", "Six nights under Namibia's dark skies p. 53", "Is telescope making dead? p. 60", and "Astronomy tests two all-sky cameras p. 62". The cover is set against a background of various planets and stars.

Free Floating Planet Events have $t_E < 2$ days

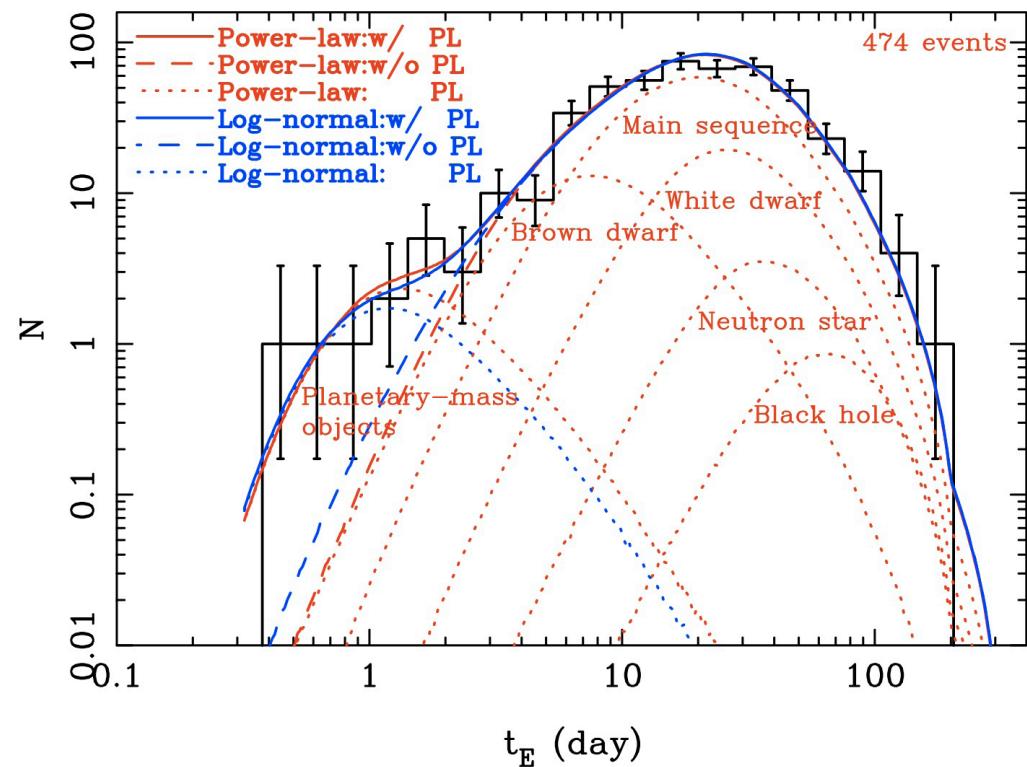
$$t_E = \frac{R_E(M,D)}{v_t} \sim \sqrt{M/M_J} \text{ day}$$

~ 20 days for stars

M : lens mass
 M_J : Jupiter mass
 D : distance
 v_t : velocity



$\sim 1.8 \times$ as Many FFP as stars!



Sumi et al. 2011

WFIRST can detect Earth-mass FFP

Formation Scenarios

1. Formed like stars through gas cloud collapse (sub-brown dwarfs)

- Hard to form Jupiter-mass objects
- Planetary-mass sub brown dwarf can explain only 1 or 2 short events.
- Abrupt change in mass function at Jupiter
- Unlikely

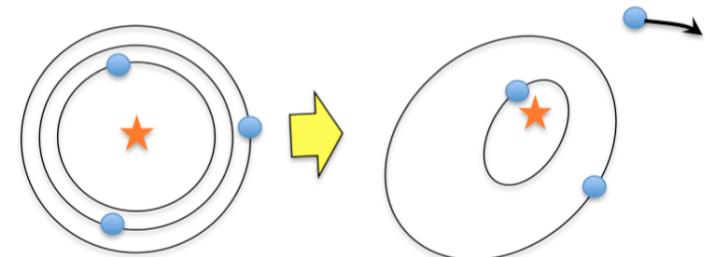


2. Formed around a host star, and then removed from orbit

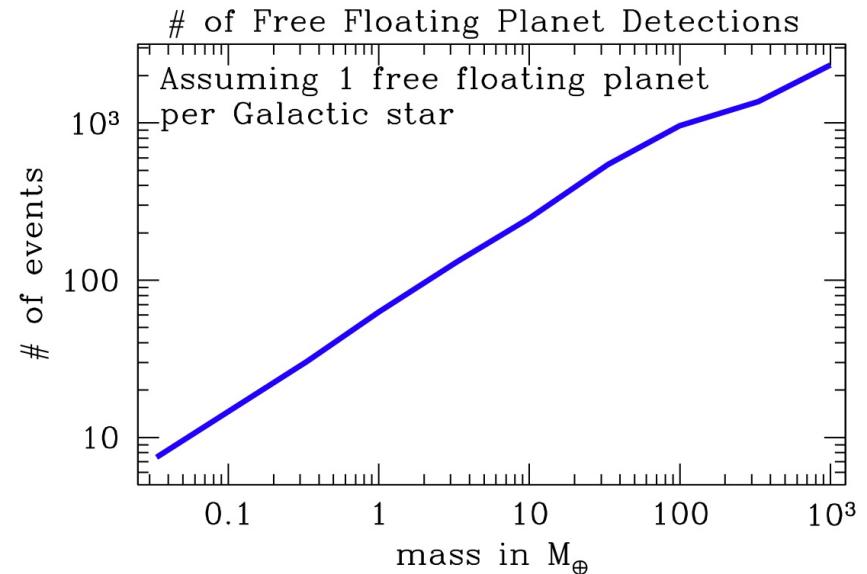
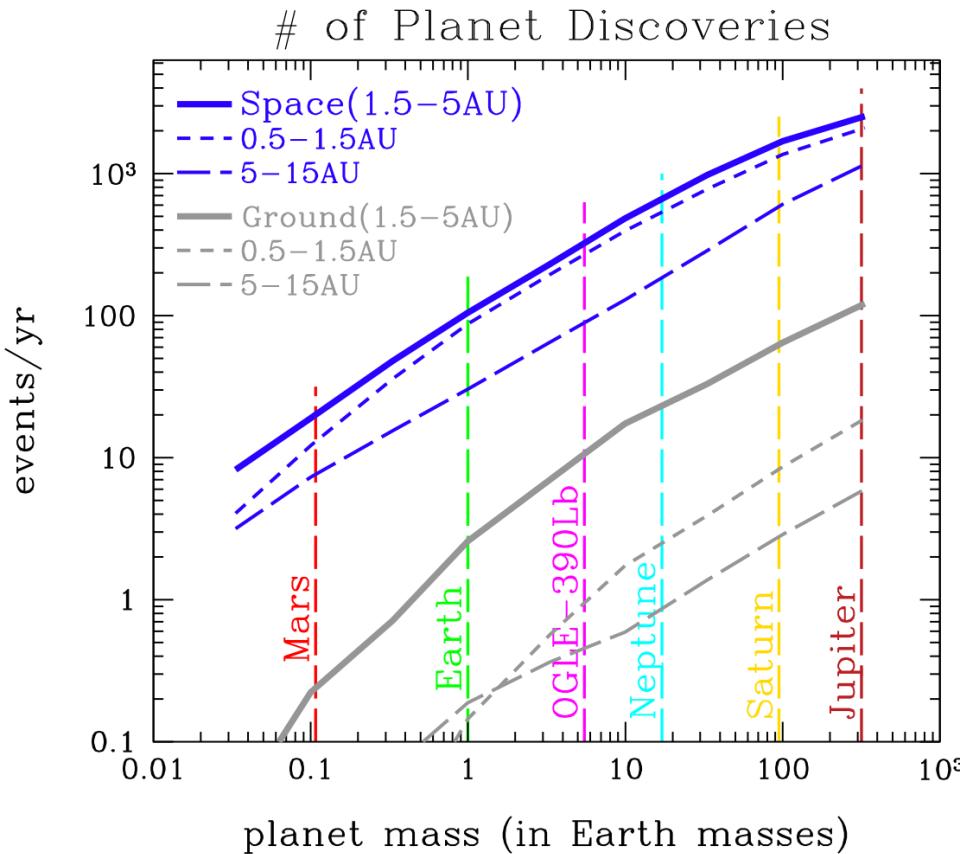
- Stellar death – mass loss



- Gravitational scattering
 - By a star – binary system or dense cluster
 - by a planet
 - Evidence:
 - Hot Jupiters orbiting hot stars have high obliquities
(Winn et al. 2010, Triaud et al. 2010)
 - Hot Jupiters are alone (Latham et al. 2011)
 - No desert for short-period super-earths
(Howard et al. 2010)
 - scattering more important than planet-disk interactions



WFIRST's Predicted Discoveries



Using a slightly different simulation than in the WFIRST report.

